# Non-Micropipe Dislocations in 4H-SiC Devices: Electrical Properties and Device Technology Implications

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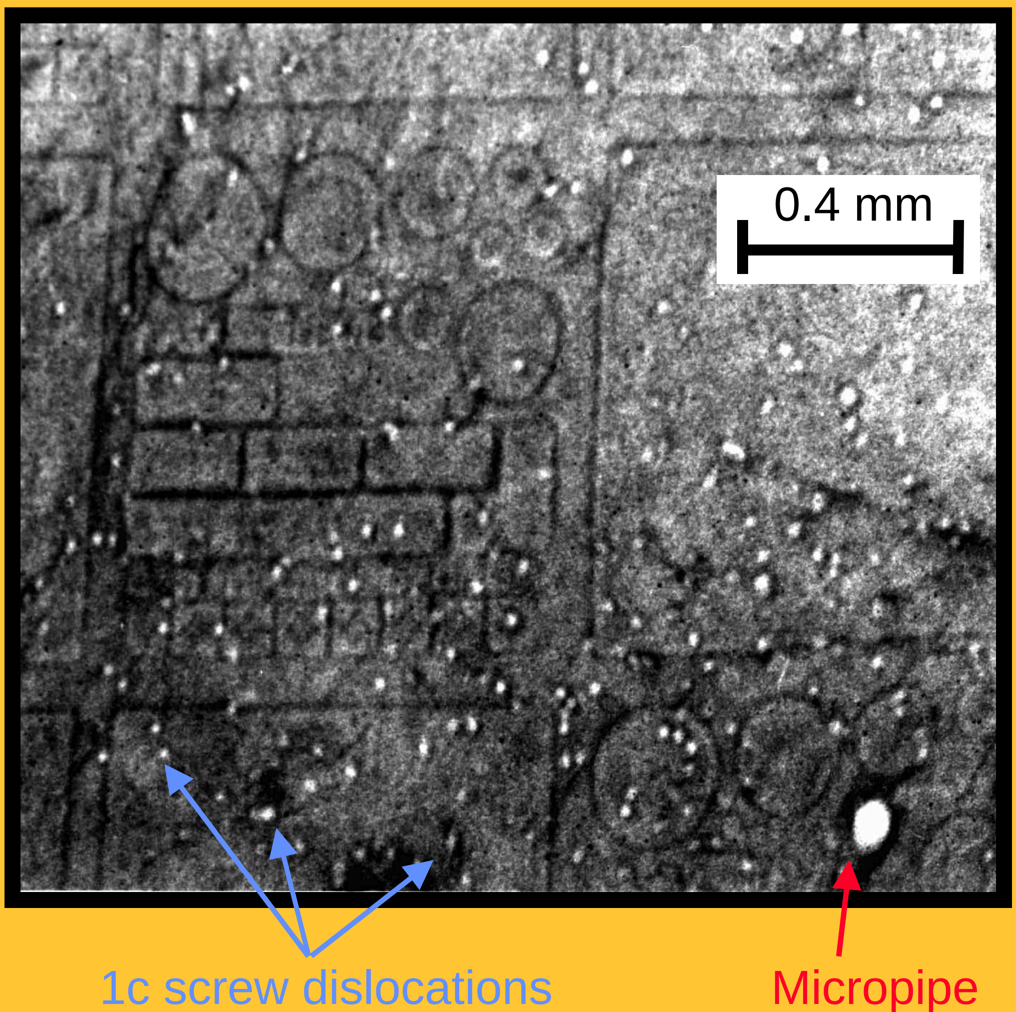
# Non-Micropipe Defects in SiC Wafers

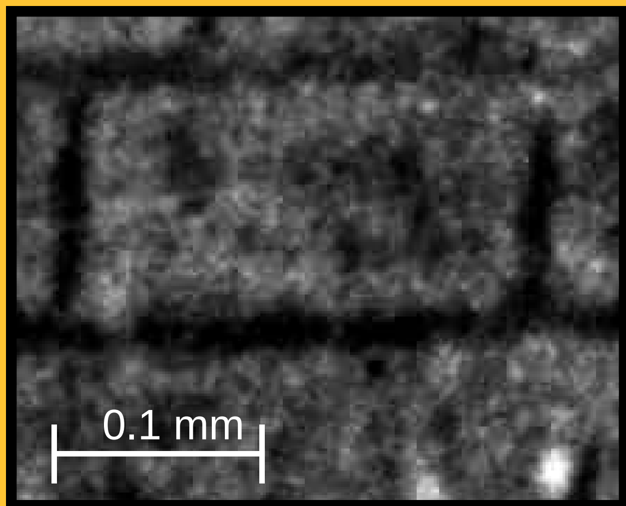
X-Ray Topographic Image of
4H-SiC Wafer Section



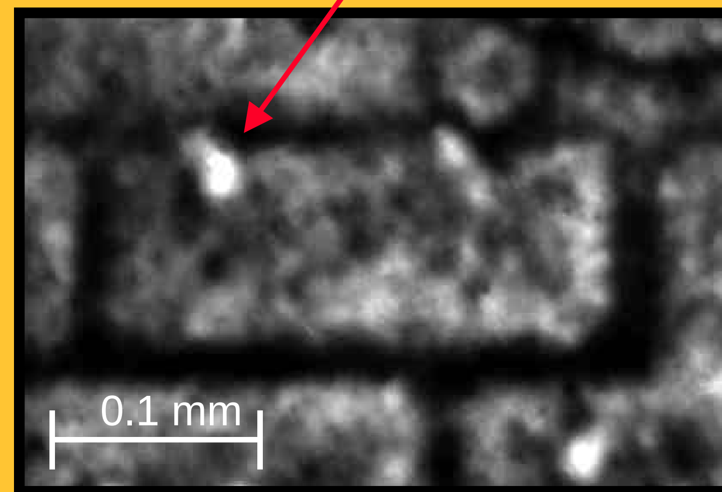

## Elementary Screw Dislocations

- Observable by Synchrotron White Beam X-Ray Topography (SWBXT).
- Non-hollow (closed) core.
- Screw Dislocations of Burgers vector = 1c.
- Densities of 3000 - 15000 / $cm^2$ in commercial SiC wafers (~ 100 X micropipe densities).
- Propagate into epilayers.
- Not as detrimental to electrical device characteristics as micropipes.

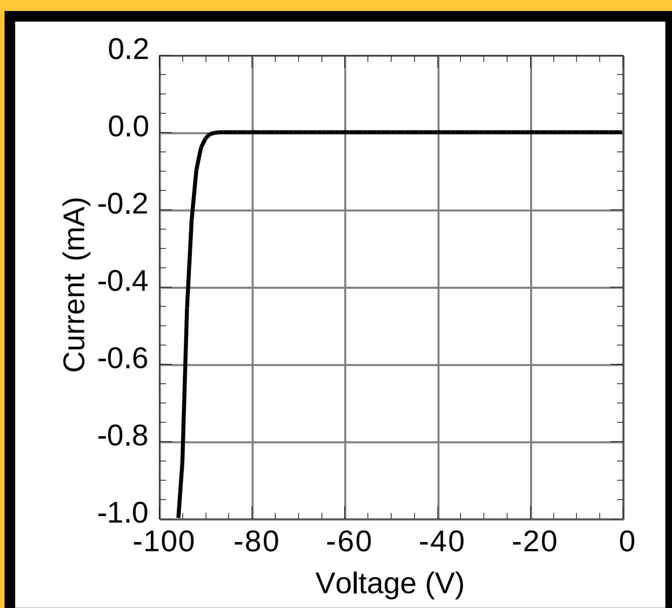
## Diode without 1c screw dislocation

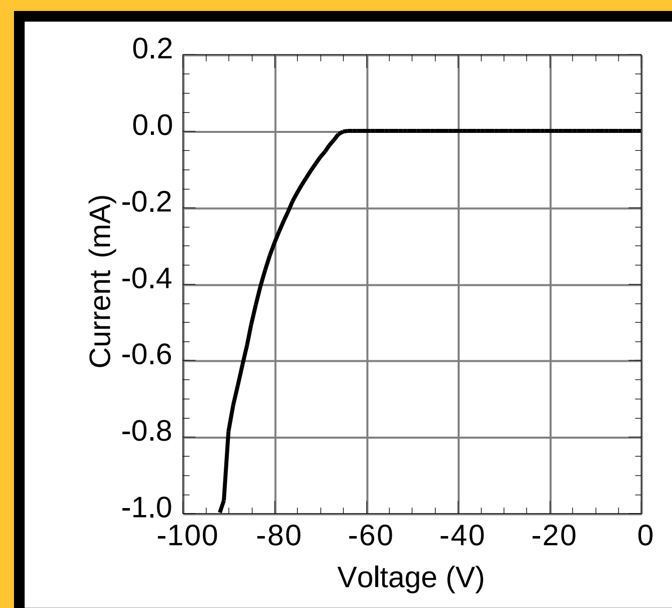



## Diode with 1c screw dislocation




X-Ray Topographic Images of Rectangular Diodes on Same Wafer.

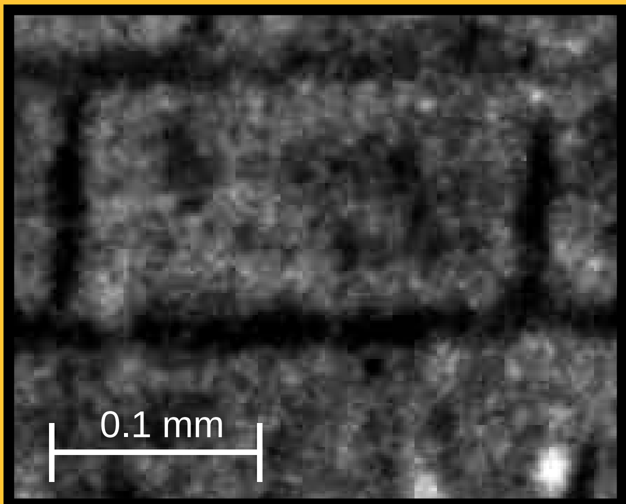



Reverse I-V Characteristics ($T_A$ = 300 K)

## Breakdown Microplasma Corresponds to 1c Screw Dislocation

Diode without 1c screw dislocation

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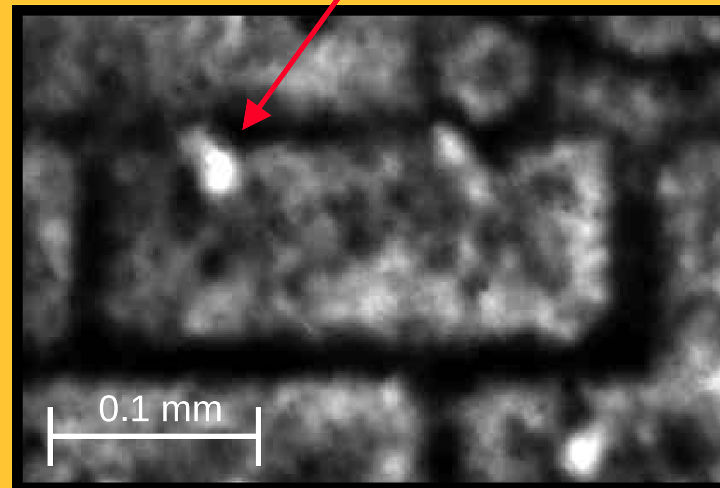
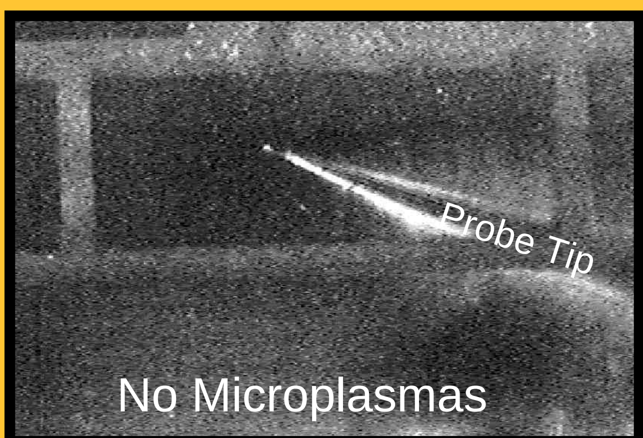
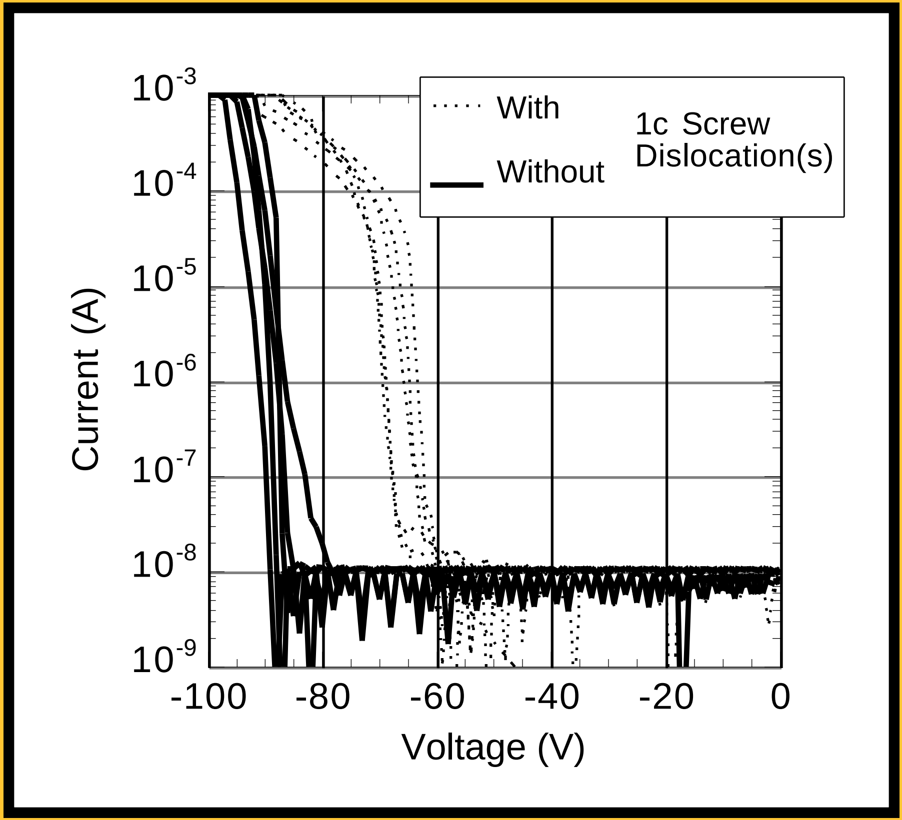
Diode with 1c screw dislocation

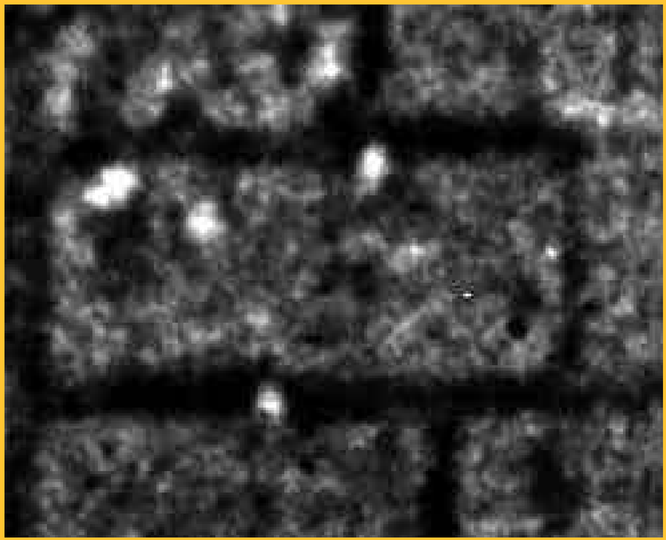


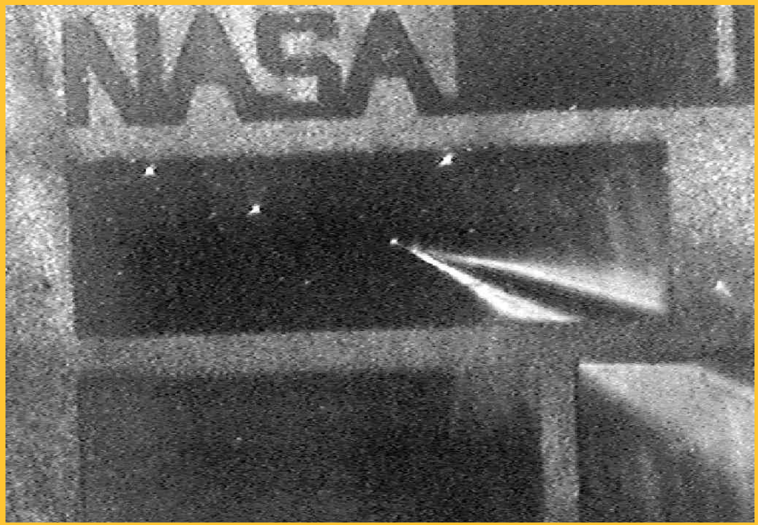




Low-light Optical Micrographs of Breakdown-Bias Luminescence

Without exception, every diode that SWBXT identified as containing an elementary screw dislocation exhibited degraded reverse I-V and microplasmic breakdown.

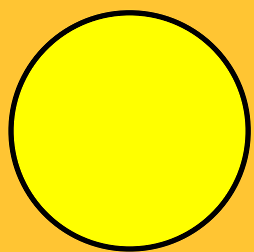




# Breakdown Properties & Power Device Reliability*

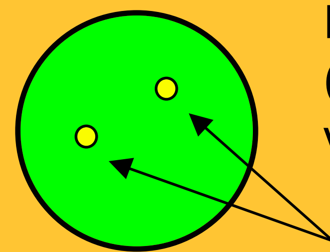
Diode Area



Breakdown current (energy) evenly distributes over the entire device area.

- Positive Temperature Coefficient of Breakdown Voltage Behavior
- Devices withstand very high energy before damage or failure occurs.
- Large Safe Operating Area.
- High immunity to system overvoltage glitches, EMP, lightning, etc.
- Very high reliability power devices.

Diode Area



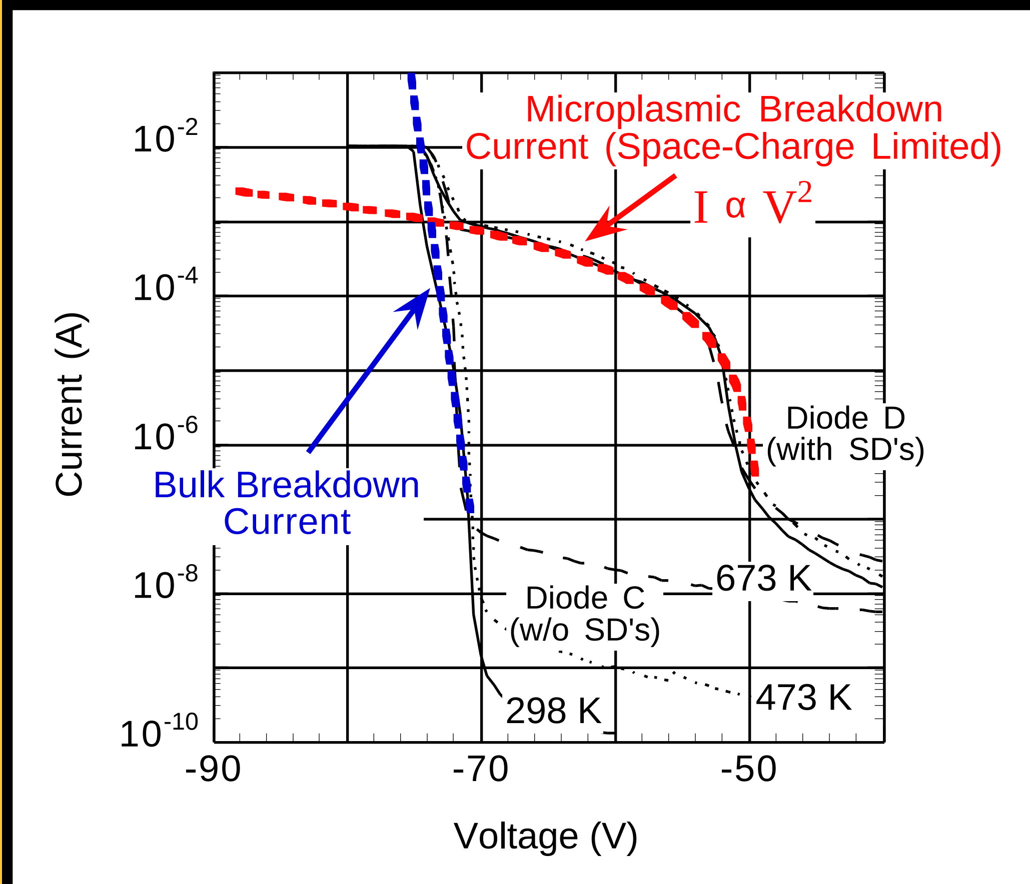
Breakdown current (energy) localized to very small area(s).

Current Filaments

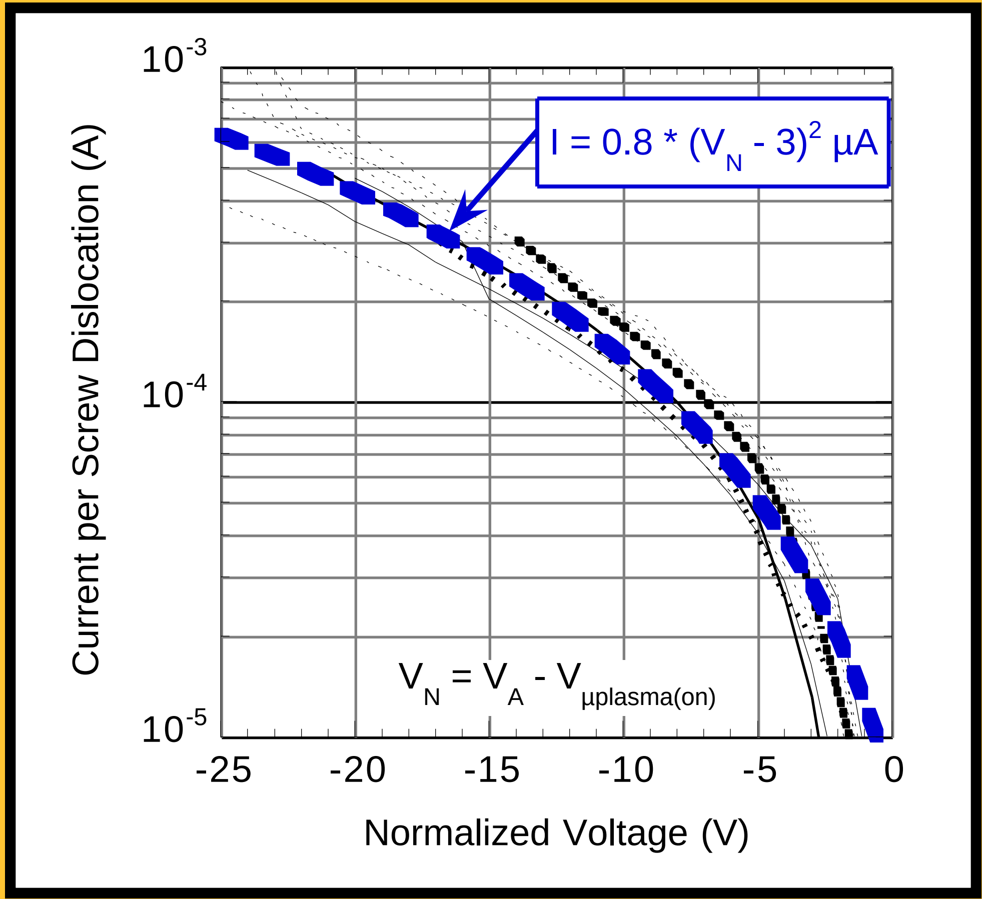
- Negative Temperature Coefficient of Breakdown Voltage Behavior
- Devices withstand much less energy before damage or failure occurs.
- Reduced Safe Operating Area.
- Lower immunity to system overvoltage glitches, EMP, lightning, etc.
- Compromised power device reliability.

*Paraphrased from Bell Labs EMP Handbook, Expired MIL STD's 19500 & 461, and other literature sources.

# Microplasma vs. Bulk Breakdown Current



# Breakdown Microplasma I-V




Microplasmic breakdown follows Space-Charge Limited (SCL) behavior

# Quantitative Measurement of Rectifier Breakdown Reliability*

*Bell Labs EMP Handbook, Expired MIL STD's 19500 & 461,
Wunsch & Bell, IEEE Trans. Nucl. Sci. 15 p. 244 (1968), & other literature sources.

## Semiconductor junction energy to fail

A fundamental parameter impacting high power device
Safe Operating Area (SOA), rectifier reliability.

## Measurement:

Reverse-bias pulse breakdown testing of diode rectifiers.
Device heats up as high breakdown power dissipated at junction.

Increase pulse amplitude and/or duration until device failure reached.
Failure is thermal - critical failure temperature reached inside device.
- Second breakdown
- Physical damage to semiconductor or device contacts

# Wunsch-Bell Pulse-Breakdown Thermal Failure Model*

Wunsch & Bell, IEEE Trans. Nucl. Sci. 15 p. 244 (1968).

To first order, thermal junction failure follows relation:

$$P_D = \sqrt{\pi \kappa \rho C_p} \left[ T_m - T_i \right] t^{-1/2} \ \mathrm{kW/cm^2}$$

$P_D$ = Breakdown power density ($kW/cm^2$) dissipated by junction during bias pulse.

t = Breakdown bias pulse duration (µs), 0.1 µs < t < 20 µs non-adiabatic heating.

$T_m$ = Critical failure temperature where physical device damage occurs.

$T_i$ = Initial device temperature prior to breakdown bias pulse.

$\kappa$, $\rho$, $C_p$ = Semiconductor thermal conductivity, density, & specific heat.

- Experimentally valid approximation for wide range of silicon pn rectifiers.
- Localized breakdown greatly reduces failure power density.

# Wunsch-Bell Pulse-Breakdown Thermal Failure Model*

*Wunsch & Bell, IEEE Trans. Nucl. Sci. 15 p. 244 (1968)

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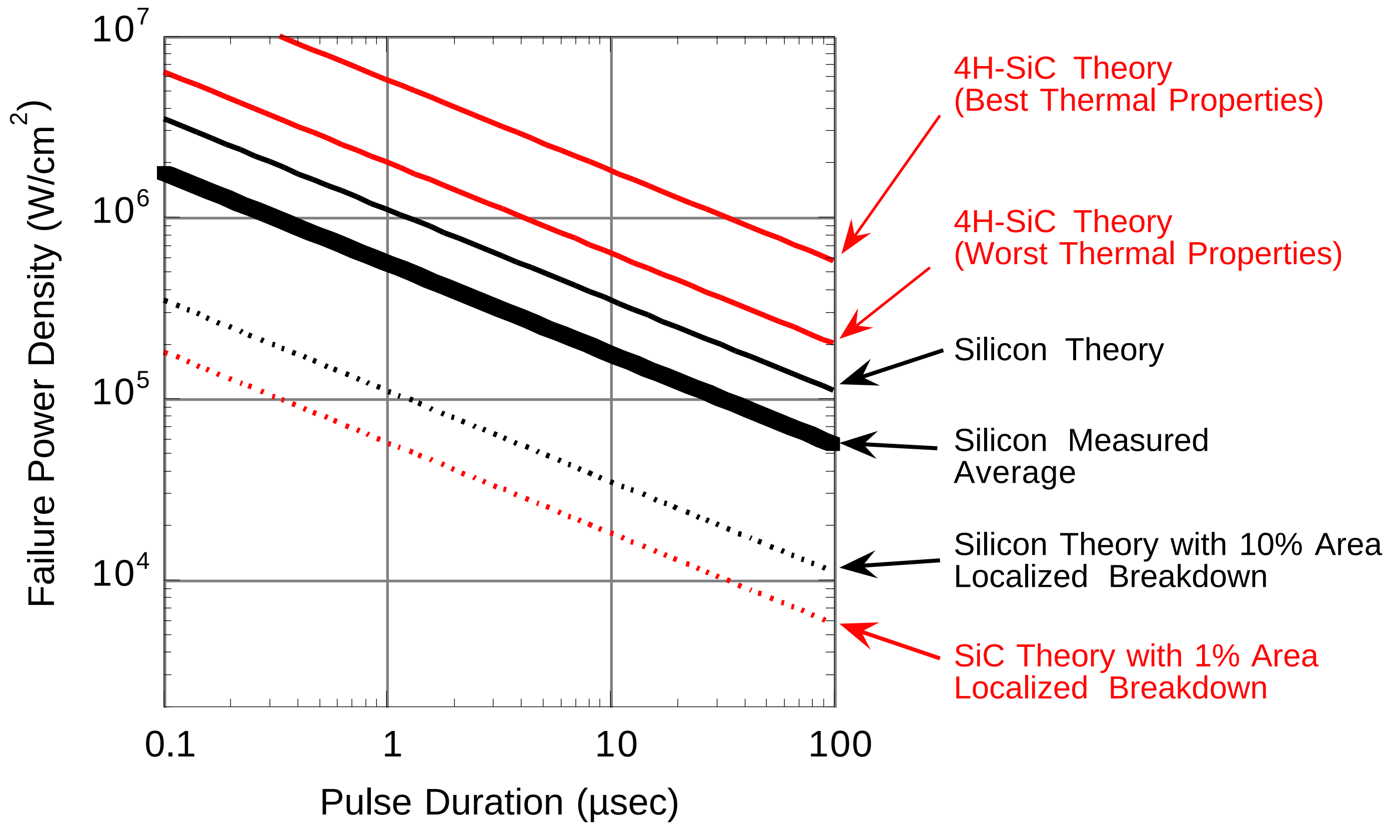
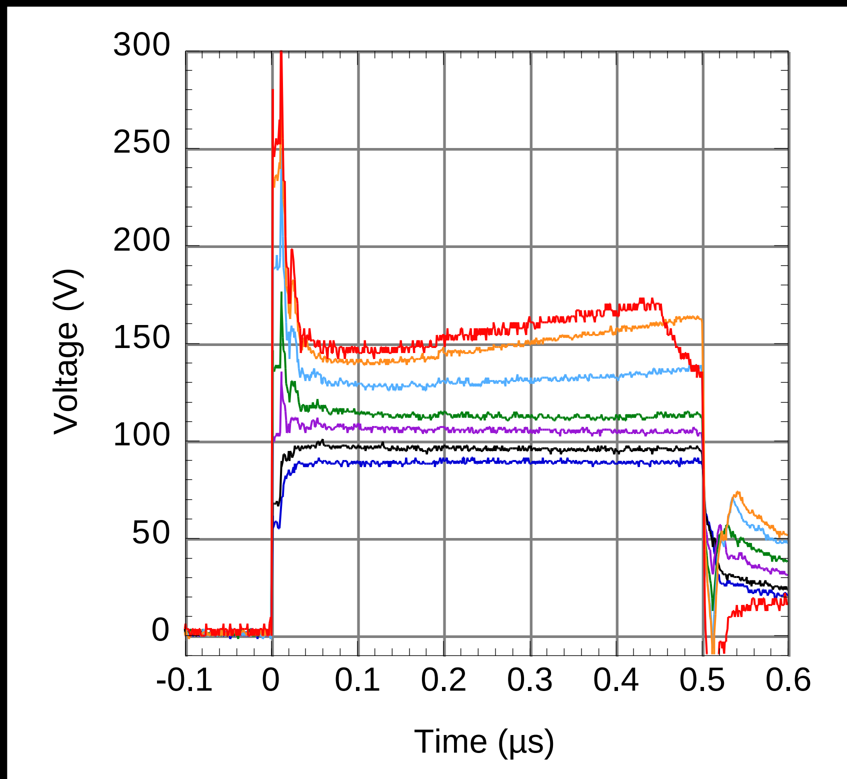
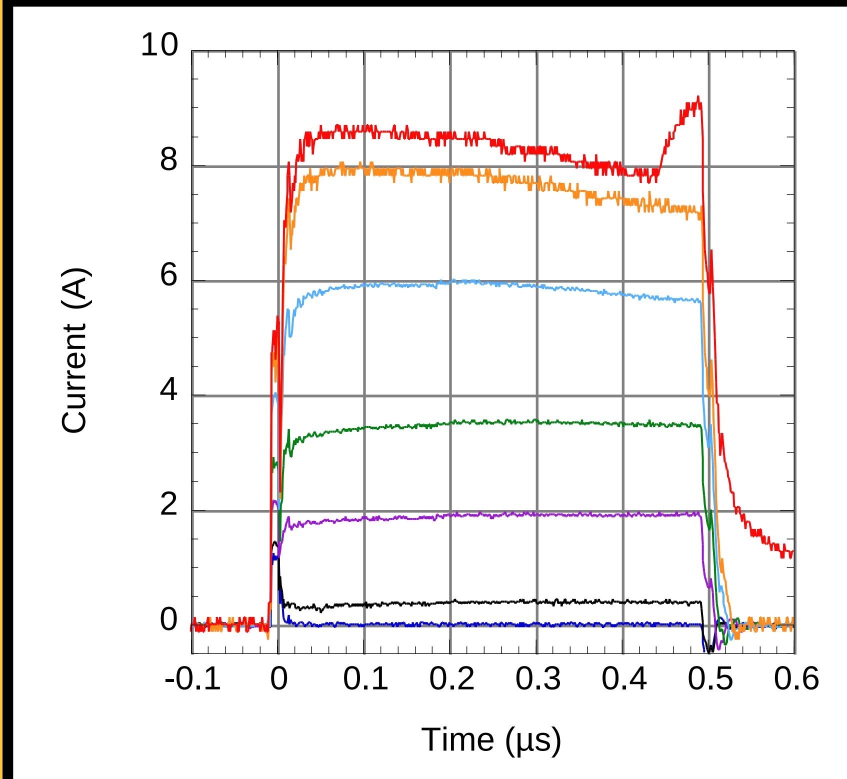


# INSTRUMENTATION & CONTROL TECHNOLOGY DIVISION

## 4H-SiC PN Diode Reverse Breakdown Pulse Testing

(Area = 3.14 x $10^{-4}$ $cm^2$, $V_{BKDN(DC)}$ = 80 V)



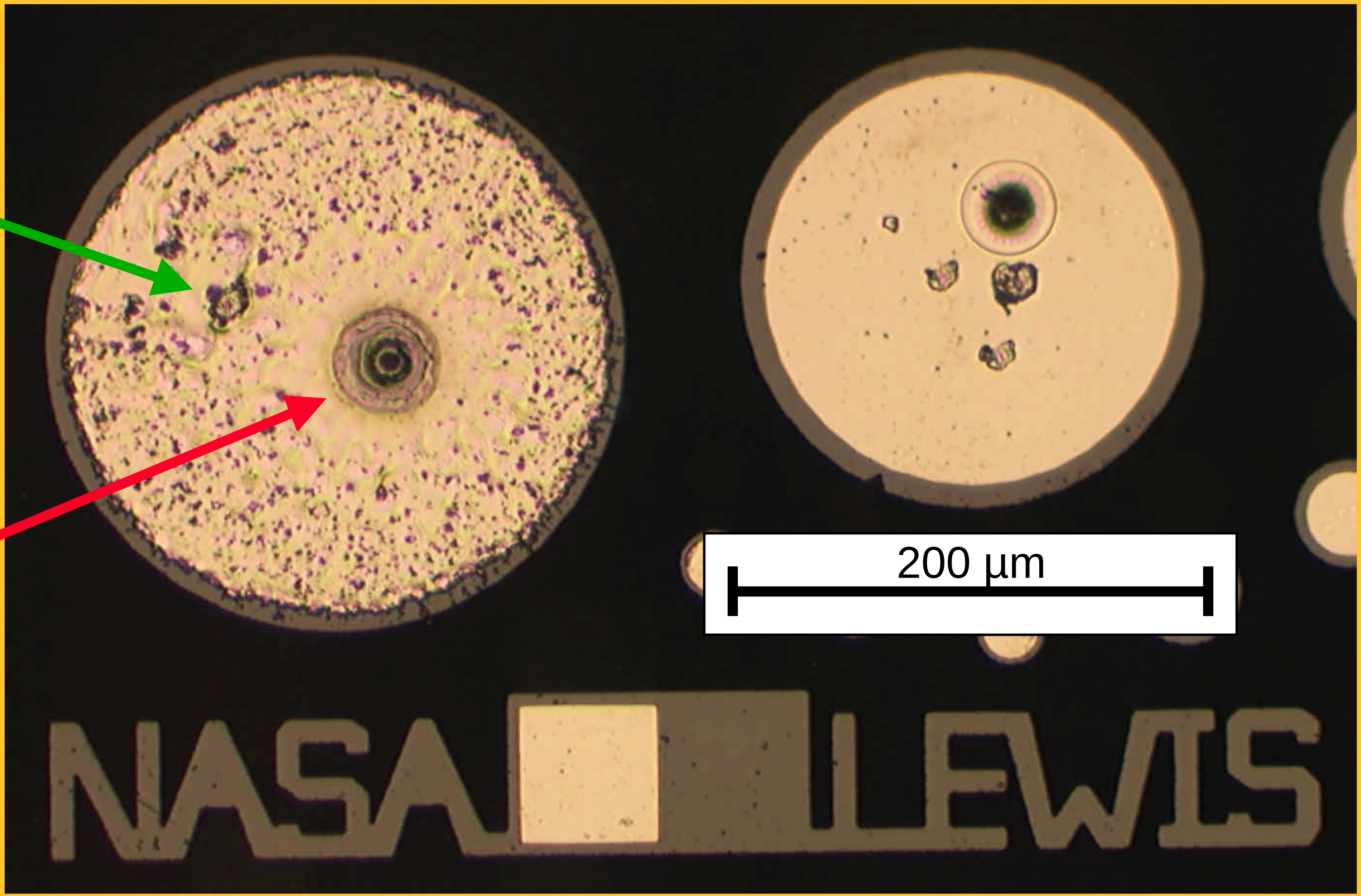




Devices containing elementary screw dislocations exhibit positive temperature coefficient of breakdown voltage behavior.

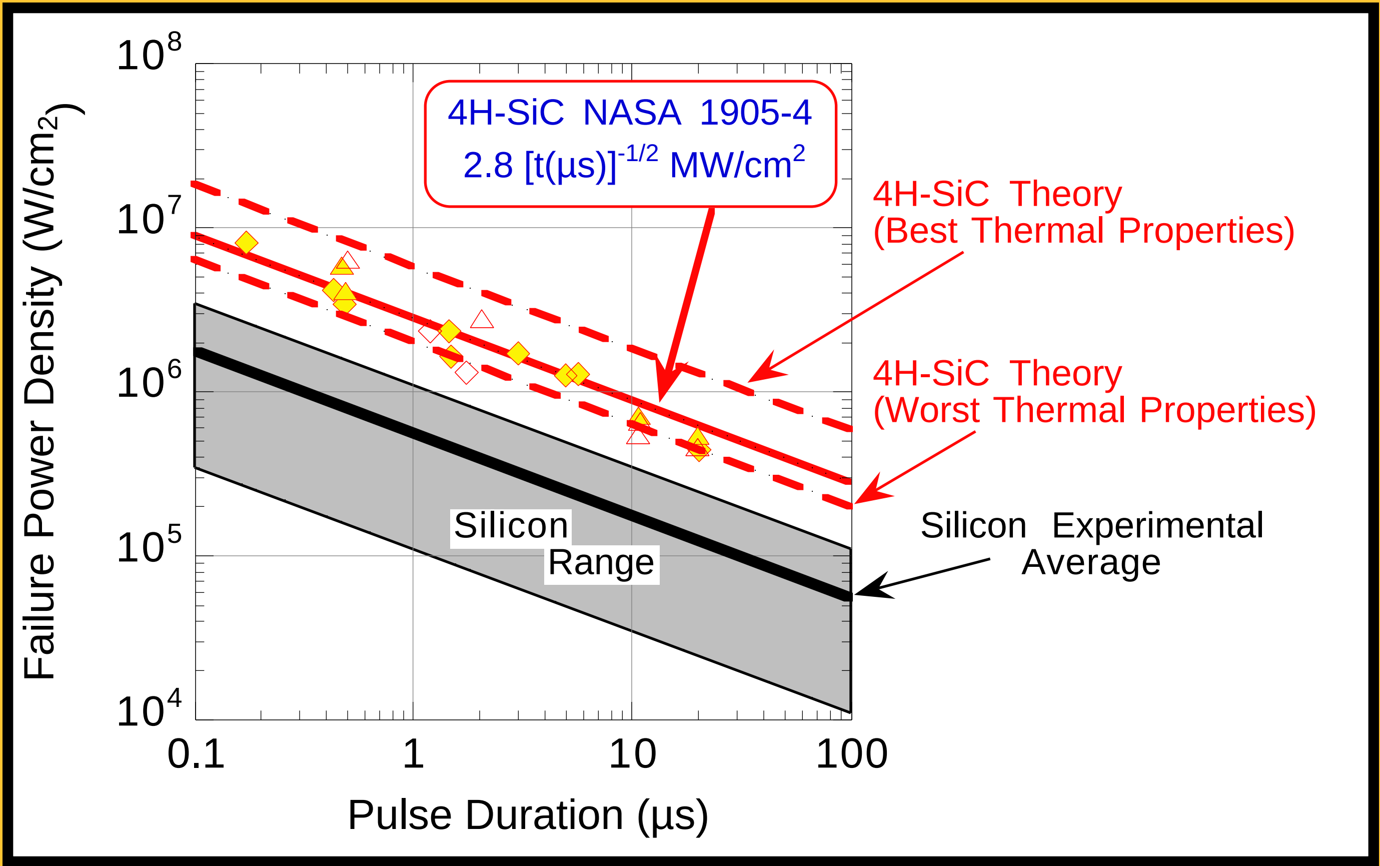
## 4H-SiC pn diodes following pulse-breakdown failure

Probe Contact Location

Junction Failure Location



# 4H-SiC PN Diode Experimental Results
(NASA Sample 1905-4)




Elementary screw dislocations did **not** significantly impact the breakdown failure power density of these 4H-SiC diodes.

# Discussion

Elementary screw dislocations did **not** significantly impact the breakdown failure power density of these low-voltage 4H-SiC pn diodes.

**HOWEVER**, above result does **not** necessarily apply to:

- Higher voltage 4H-SiC pn diodes (1 kV - 10 kV).
- 4H-SiC Schottky diode rectifiers.
- Bipolar gain 4H-SiC device structures (Thyristors, IGBT's, etc).

These structures could prove more vulnerable to localized breakdown at elementary screw dislocations.

- Silicon microplasma current relatively insensitive to junction width. Higher SiC microplasma power density in higher-voltage SiC junctions?
- Silicon bipolars and Schottky's fail at lower power densities that Si pn diodes.

**Further pulse-breakdown testing of various SiC device structures is needed.**

# Summary

First successful measurement of 4H-SiC junction energy to fail characteristics.

- Classic $P \propto t^{-1/2}$ behavior observed for non-adiabitic pulsewidths.

Experimental 4H-SiC breakdown power density ~ 5X larger than silicon.

Elementary screw dislocations did not degrade breakdown reliability of low-voltage (< 250 V) 4H-SiC pn junction diodes.

- Space-charge effects limit current of localized breakdown at elementary screw dislocation.
- Positive temperature coefficient breakdown behavior observed in diodes containing elementary screw dislocations.

Impact of elementary screw dislocations on other SiC device topologies remains to be investigated.